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THE TECHNOLOGY OF ELECTRIC SPARK CUTTING OF METALS

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In recent years an electric method of metal cutting has been perfected and introduced in Soviet plants. The system (Figure 1) proposed by Stalin Prize Laureate B. P. Lazarenko is generally taken as the basis. This system is the same as the now obsolete system of electric spark radio transmitters.

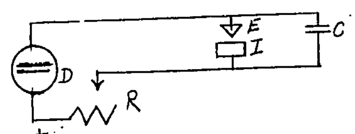

Figure 1

D -- dc source. C -- condenser. E -- electrode connected to the negative pole of the current source; I -- work piece to which the positive pole of the current source is connected through resistance R.

The electrode and the work piece are immersed in a liquid medium (kerosene, oil, or water). Under the action of the spark discharge (from the work piece), splinters of metal are chipped off and cast aside. The electrode, generally made of brass, disintegrates at the same time.

The disadvantages of this system are its low productivity, high consumption of electrodes, and high consumption of electric power.

In drilling holes 5 mm in diameter in chrome steel with a hardness of $H_B = 352$ on the described electric spark apparatus, the efficiency is one-tenth that of mechanical cutting, the wear and tear on the equipment is 20 times greater, and the consumption of electric power is 10 times greater.

However, carefully conducted research shows that the technological and economic indices in electric spark cutting of metals can be considerably improved in a number of cases.

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As is well known, the chief index of the degree of perfection of the metal cutting process is the specific productivity. By specific productivity, we mean the amount of metal converted into shavings in 1 min by a portion of the cutting edge 1 mm in length. Determining the specific productivity for the electric spark method of cutting is complicated by the lack of a clear concept of the cutting edge. We have agreed to consider that the "cutting edge" of a spark slightly exceeds the diameter of the hole made by the spark. The effective length of the edge of one electrode in the systems we selected was equal to approximately 2 mm. By aligning the electrodes it is possible to obtain a continuous cutting edge of any length. It is well known that with a capacitance $C = 500$ mfd, $u_0 = 220$ v, and $I_k = 40$ a, the productivity of the electric spark cutting is 330 cu mm/min. Consequently, the specific productivity is:

$$q = \frac{330}{2} = 165 \text{ cu mm/min}$$

Comparison of this quantity with the specific productivity of mechanical cutting (Table 1) shows that the process of electric spark cutting is not inferior to any kind of mechanical cutting in efficiency.

Table 1

Type of Cutting	Specific Productivity (cu mm/min)
Milling	70
Drilling	120
Grinding	2100

Analysis of the electric spark cutting processes shows that its cycle may be divided into two periods. In the first a condenser is charged, and in the second the condenser is instantly discharged with a spark that breaks up particles of the work piece (and of the electrode) into fine metallic dust. The charging period may be considerd as accessory time, by analogy with mechanical cutting, and the discharge as machine (operating) time.

Charging the Condenser

Condenser C (Figure 1) is the power source for the discharge. The condenser charge is expressed by the equation:

$$u = u_0 \left(1 - e^{-\frac{t}{RC}}\right) \tag{1}$$

where u is the voltage on the plates of the condenser during the period of time t from the beginning of the charge; u_0 is the supply voltage in v (generator); e is the base of the natural logarithm; R is the resistance of the rheostat (in ohms) during condenser charging; C is the condenser capacitance in farads; and t is the time from the start of charging in sec.

The quantity RC indicates the rate of increase of the voltage u on the condenser plates.

With the lapse of time t_0 from the start of charging, the voltage $u = 0.99\, u_0$; in that case,

$$t_0 = 4.6\; RC = 4.6\, \frac{u_0 C}{I_k} \tag{2}$$

where I_k is the short circuit current of the electrodes (Table 2).

Table 2. Values of I_k in Electric Spark Cutting of Metals

C (mfd)	5	25	50	100	200	300	400	500
I_k (a)	0.8	4	8	13	23	32	40	45
$\frac{C}{I_k}$	6.2	6.2	6.2	7.8	8.7	9.4	10	11.1

To ascertain that the adopted formulas (1) and (2) are correct, experiments were made in using the spark process on the surface of a cylinder in a spiral pattern. For this purpose a cylinder (Figure 2) was fixed on the high-speed spindle of a lathe, and current was fed to the cylinder from the positively charged condenser plate. The brass electrode, connected with the negatively-charged condenser plate, was attached to a support. The spark gap between the brass rod and the cylinder was filled with kerosene. The spark discharges formed circular craters on the cylinder. As the cylinder rotated and the

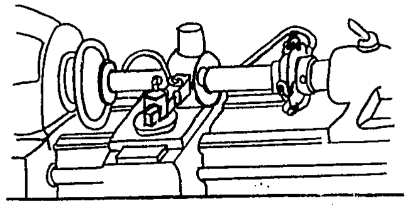

Figure 2. Installation for Recording the Electric Spark Process

brass rod moved along the cylinder axis, the craters were disposed in a spiral line at some distances from each other. The experiment showed that the diameter of the crater conformed to the law of exponential functions:

$$d = d_0 \left(1 - e^{-\frac{t}{RC}}\right) \tag{3}$$

where d is the diameter of the crater (in mm) developed after the discharge of the condenser charged over the period of time t, d_0 is the diameter of the crater (in mm) obtained after the discharge of the fully-charged condenser.

By measuring on the cyliner the least distance between craters with diameter d_0 and by subsequent calculation, the time interval t_0, necessary for the full charging of the condenser was established:

$$t = \frac{a \cdot 60}{\pi D n} \tag{4}$$

where t is the time between consecutive discharges (calculating along the spiral line) in sec; a is the distance between adjacent craters in mm; D is the diameter of the cylinder in mm; and n is the rpm of the cylinder.

The charging time of the condenser, established in experiments with an accuracy of 3%, coincided with the charging time obtained by calculation according; to formula (2).

The conditions used in practice (Table 2) enable us to establish that the charging time varies from $3 \cdot 10^{-3}$ to $11 \cdot 10^{-3}$ sec (Table 3).

Table 3. Charging Time t_0 of Condenser in Sec

C (mfd) Voltage (v)	5	25	50	100	200	300	400	500
120	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$3.9 \cdot 10^{-3}$	$4.4 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$	$5 \cdot 10^{-3}$	$5.5 \cdot 10^{-3}$
220	$5 \cdot 10^{-3}$	$6 \cdot 10^{-3}$	$6 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$8.8 \cdot 10^{-3}$	$9.5 \cdot 10^{-3}$	$10 \cdot 10^{-3}$	$11 \cdot 10^{-3}$

Consequently, the frequency for charging up to peak voltage may vary from 100 to 300 cps.

Condenser Discharge Time

The intensity of the condenser discharge current conforms to the law expressed by the formula

$$I = -\frac{u_0}{R} e^{-\frac{t}{RC}} \qquad (5)$$

The quantity RC denotes the rate of decrease in the intensity of the current, and it is called the time constant of the circuit (discharge).

The current intensity $I = 0.01 \frac{u_0}{R}$ that is, practically speaking, the discharge can be considered completed to within 1% upon the lapse of time t_0.

Resistance R in the discharge circuit consists of the sum of the resistances of the condensers, the connecting busbars, and the cable; resistance of the spark is negligible.

For any MKV-type condenser with a capacitance of 0.5 mfd the resistance is 1.28 ohms. For a bank of condensers with a capacitance of 100 mfd of the ohmic resistance of the condensers is $\frac{1.28}{2.00} = 6.4 \cdot 10^{-3}$ ohms. In general, the resistance of the discharge circuit $R = 6.6 \cdot 10^{-3}$ ohms. The time of the discharge is

$$t_0 = 4.6\ RC = 4.6 \cdot 6.6 \cdot 10^{-3} \cdot 100 \cdot 10^{-6} \quad 3 \cdot 10^{-6} \text{ sec.}$$

To make sure that the calculated time of discharge corresponds to practice, experiments were conducted on the development of a spark discharge on the surface of a cylinder in a spiral pattern. The method was the same as that described above. In producing the spark discharge, a cylinder 25.4 mm in diameter was rotated at high speed. The erosion of the crater lengthwise was noted only at above 1,500 rpm, which corresponds to time t_0, calculated by formula (4)

$$t_0 = \frac{a \cdot 60}{D \cdot n} = \frac{0.01 \cdot 60}{3.14 \cdot 25.4 \cdot 1500} = 5 \cdot 10^{-6} \text{ sec,}$$

where a is the erosion of the crater, noted under the microscope, in mm.

If the condenser capacitance is over 200 mfd, its high-power discharge is attenuated somewhat more slowly than could be expected on the basis of the calculations. Thus, if the condenser capacitance $C = 550$ mfd, the calculated time $t_0 = 2 \cdot 9 \cdot 10^{-6}$, while the actual life of the spark is $250 \cdot 10^{-6}$ seconds.

To point out the nature of the phenomena occurring in the course of $250 \cdot 10^{-6}$ sec, they were recorded on the surface of a processable cylinder. The peripheral speed of the cylinder was set at over 2,000 m/min (v = 36 m/sec). The spark process with C = 300 mfd extended for $191 \cdot 10^{-6}$ sec. In the developed form the spark process proved to consist of five discharges consecutive in time and decreasing in intensity.

The life of the first main discharge proved to be $47.5 \cdot 10^{-6}$ sec, which is considerably closer to the calculated time of discharge. The difference between the calculated and actual time may be explained by various causes, among which the effect of self-inductance can be considered the most important. If there are a great number of condensers in the discharge circuit, the total self-inductance of the condensers is the cause of formation of "extra" contact currents I, given by the equation

$$I = -\frac{u}{R} \cdot e^{\frac{R}{L}t} \qquad (6)$$

where I is the extra (induced) contact current flowing counter to the direction of the discharge and impeding the discharge process, and L is the self-inductance of the discharge circuit.

The presence of self-inductance in the discharge circuit is also the cause of the formation of extra currents when the circuit is broken and they conform to the same rule expressed by formula (6), but with reversed sign.

The extra current of disconnection is in the same direction as the condenser discharge and lengthens the time of passage of the current. These induced currents are equal in quantity but opposite in sign. Consequently, the extra currents do not increase or decrease the general amount of discharged electricity; they merely extend the time of the discharge. This is the chief, but not the only, cause of a certain discrepancy between the actual and calculated times of discharge.

The most important components determining the nature of the discharges are self-inductance and the resistance of the discharge circuit.

Intensity of the Discharge

The work of the discharge is determined by the well-known formula

$$A = \frac{1}{2} C u^2 \qquad (7)$$

where A is the work of the discharge in joules.

The data obtained on the basis of this formula are given in Table 4.

Table 4. Work of One Discharge in Joules

C (mfd) Voltage (v)	5	100	500
120	0.036	0.720	3.600
220	0.121	2.420	12.100

The energy of the electric discharge pulse and the magnetic field accompanying it acts in a very short interval of time. The motor forces which act upon the metal particles attain very high values. The metal particles are chipped from the work piece in a whole conglomerate of crystals and are scattered in all directions with great force, leaving an irregular surface on the metal covered with an intercrystalline surface.

The discharge is the more effective the shorter its time of action.

Productivity of a Single Electric Spark Discharge

The external manifestation of the effectiveness of a discharge is the appearance on the work piece of a circular crater, the depth of which is 0.03 d (d is the diameter of the crater). The bottom of the crater is the irregular surface on which the crystal grains were held, as in a cement, in the intercrystalline substance before the discharge. The edges of the crater are not subjected to the direct action of electromagnetic forces. The disintegrations on the periphery of the crater are traces of the passage (dragging) of metal particles from the bottom of the crater, and therefore the disintegration on the periphery of the crater takes place, as is usual, by metallic crystals.

The crater (or hole) is, approximately, a cylindrical depression with a flat bottom. The diameter of a crater depends upon the voltage on the plates of the condenser and the condenser capacitance (Table 5).

Table 5. Crater Diameters (in mm) for Discharges of a Fully Charged Condenser

(Compiled on Basis of Experiments)

C (mfd) Voltage (v)	5	50	100	400	500
80	0.10	0.46	0.72	1.50	1.60
160	0.25	0.80	1.22	1.86	1.90

The volume of the metal, if we consider the depth of the crater as 0.03 d, is

$$q_0 = \frac{\pi}{4}(0.03)\, d^3 = 0.0235\, d^3 \text{ cu mm/discharge} \quad (8)$$

where q_0 is the volume in cu mm/discharge.

Determining the magnitudes of the diameter of the crater by Table 5 and introducing them into equation (8), it is not difficult to calculate the productivity of one discharge (Table 6).

Table 6. Productivity (in cu mm) of One Discharge of a Fully Charged Condenser

C (mfd) Voltage (v)	5	100	300	500
80	0.00002	0.0088	0.0577	0.0964
160	0.0004	0.0426	0.1370	0.1607

Productivity and Power of Electric Spark Cutting Equipment

Manufacturers are interested in productivity per min, which is the total of the productivities of all the discharges. The very high indices relating to a single discharge were given above. Productivity per min depends upon

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the method of summarizing the productivity of single discharges. The productivity of electric spark cutting, with the capacitance of the condenser $C = 500$ mfd, was studied on the equipment for reproducing the spark process (Figure 2). It was proved that the charging of the condenser lasts $100 \cdot 10^{-4}$ sec, and then there is a pause of $250 \cdot 10^{-4}$ sec, and finally the discharge takes place in the course of $2.4 \cdot 10^{-4}$ sec.

The entire cycle lasts 0.03524 sec and is then repeated. As a result the number of discharges N, taking place in the experiment, was 28 per sec.

The measurements showed that each discharge scatters 0.2 cu mm of metal. Thus, the productivity per min.

$$Q = 0.2 \cdot 28 \cdot 60 = 336 \text{ cu mm/min}$$

which corresponds to actual productivity in manufacturing.

It is evident from the experimental data given that during 0.7% of the entire time, the equipment for electric spark cutting produces useful work; 28.3% of the time is lost in charging the condenser, and during the remaining 71% the equipment is in a state of "pause."

The power of the equipment may be expressed by the formula

$$W = \eta\, u_0 I \qquad (9)$$

where η is the coefficient of utilization of the power of the equipment, which depends upon the capacitance of the condenser and a number of other conditions.

For the given conditions of this experiment, $W = 0.03 u_0 I$.

Increasing the power on the basis of formula (9) by increasing the voltage is permissible only within the limits determined by considerations of safety. The power may be increased by increasing the current I, but with excessive increase of the latter the spark discharge is transformed into another process with all its consequences.

The relationship (Table 2) of the intensity of the short circuit current to various magnitudes of condenser capacitance has been established in practice. Taking η as 0.03, we obtain the values of the expended power (Table 7).

Table 7. Useful Power of Electric Spark Installation in W (For $\eta = 0.03$)

C (mfd) / Voltage (v)	5	100	500
120	3.2	52	180
220	5.6	91	315

In experiments to determine the consumption of electric power in the ac supply circuit (according to a meter hooked into the ac motor circuit of the converter) after deducting the no-load power, large magnitudes of power consumption were obtained. For a hole 5.05 mm in diameter with a length of 3.5 mm (in high-speed steel), 20 whr were expended. Since the hole actually had a diameter of 5.3 mm, the volume of dispersed metal is 77 cu mm.

Allowing for the fact that 20 whr = 20 · 3571 = 71,420 joules, we determine the specific consumption of electric power:

$$W = \frac{71,420}{77} = 928 \text{ joules/cu mm}$$

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According to the calculation in Table 4, the specific consumption of electric power for metal dispersion of 0.2 cu mm volume is

$$W = \frac{12.1}{0.2} \approx 60 \text{ joules/cu mm}$$

that is, one fifteenth of that indicated above.

The difference can be charged to losses of electric power in the Joule effect in the rheostats and the connecting leads. Thus, the actual consumption of power roughly corresponds to the data of Table 7 multiplied by 15 (considering the contemporary technological level of the process). The generator rating should be

$$W = u_0 \cdot I_k, \qquad (10)$$

that is, 30 times higher than the data of Table 7.

This power reserve in the generator allows for cases of short circuiting in the spark gap, which frequently occur in the cutting process.

The intensity of chip formation at the time of cutting is given by:

$$Q = \frac{q \cdot 60}{t} \qquad (11)$$

where q is the volume of metal dispersed by one discharge, in a cu mm, and t is the time of one discharge in sec.

For work with a 500-mfd condenser, we obtain

$$Q = \frac{0.2 \cdot 60}{251 \cdot 10^{-6}} = 48,000 \text{ cu mm/min}$$

In no type of mechanical cutting, with the exception of high-speed milling, is there such intensity of chip formation along 2 mm of cutting edge. However, due to time losses for pauses and condenser charging, which amount to 99.3%, the actual maximum productivity of the equipment is

$$Q = 336 \text{ cu mm/min}$$

Productivity Reserves of Electric Spark Cutting (Number of Discharges)

To increase the productivity $Q = 336$ cu mm/min it is necessary to shorten the useless pauses, which constitute 70% of the operating cycle.

The volume of metal dispersed by one condenser discharge (Table 6), multiplied by the quantity of discharges per min, gives the productivity per min. With operating conditions for the discharge of a condenser, charged to within 1% of the applied voltage without pauses, the number of discharges is determined by the formula

$$N = \frac{1}{4.6RC} = \frac{0.2174I}{u \cdot C} \qquad (12)$$

Having determined the value I from Table 2, we obtain the number of discharges per sec (Table 8).

Table 8

C (mfd) Voltage (v)	5	100	300	500
80	436	354	299	255
120	290	236	194	162
160	218	172	147	128
220	174	143	118	100

To obtain the productivity, given in Table 9, it is necessary that the discharges be produced simultaneously with the completion of condenser charging.

Table 9. Productivity Per Min (in cu mm) of Discharges of Fully Charged Condensers

C (mfd) Voltage (v)	5	25	50	100	300	500
80	0.52	10	60	187	1,000	1,475
160	5	65	160	440	1,200	1,230

In considering the curves of voltage increase during the condenser charging, doubt arises as to the value of carrying condenser charging to completion. During charging, in conformity with the law of the exponential function, the condenser voltage increases swiftly at first, and then noticeably slower. During the first half of the charging time the voltage of the condenser reaches 0.9 of the supply voltage. If the charging process is interrupted by a discharge, the number of cycles of charging and discharging may be doubled. The number of condenser charge and discharge cycles at which the electric spark cutting method is most productive can be computed mathematically.

We determine the maximum productivity by the usual method, differentiating the productivity equation and equating the productivity differential $\frac{dQ}{dt}$ to zero.

On the basis of equations (8), (11), and also (3) and (1), we obtain

$$Q = \frac{0.0235 d^3 \cdot 60}{t} = \frac{1.41 d_0^3 (1 - e^{-\frac{t}{RC}})^3}{t} = \frac{141 d_0^3 (u/u_0)^3}{RC \cdot ln(1 - u/u_0)} \qquad (13)$$

In the case of a system with maximum productivity ($\frac{dQ}{dt} = 0$) the voltage on the condenser plates reaches

$$u = 0.848\ u_0 \qquad (14)$$

where u_0 is the generator voltage of the supply circuit.

This takes place after a lapse of time

$$t = 1.84\ RC. \qquad (15)$$

On the basis of formulas (12) and (15) we obtain the maximum productivity with

$$N = \frac{1}{1.84 RC} \tag{16}$$

$$N = \frac{0.5435}{RC} = \frac{0.5435\ I_k}{u_0 C} \tag{17}$$

where I_k is the short circuit current in (Table 2); u_0 is the voltage of the supply circuit in v; and C is the condenser capacitance in farads.

Fo. the example selected above, if C = 500 mfd, $N \approx 220$ per sec.

We obtain maximum productivity by decreasing the voltage through increasing the number of discharges to N, calculated according to formula (17). The diameter of the crater is thus decreased by the same law as the voltage, and consequently, with maximum productivity

$$d \approx 0.85\ d_0, \tag{18}$$

where d is the diameter of the crater at maximal productivity in mm; and d_0 is the maximum diameter of the crater in mm (Table 5).

For the example chosen the productivity per min is

$$Q = 0.2 \cdot 0.85^3 \cdot 220 \cdot 60 \approx 1{,}600 \text{ cu mm/min.}$$

Determining the relation between the production obtained and the intensity of chip formation according to formula (11), we obtain the coefficient of the utilization of productivity of the equipment (Table 10).

Table 10. Number of Discharges (N) per Sec and the Coefficient of the Utilization of Productivity (η) at C = 500 mfd

No of Discharges and Coefficient η	In Existing Installations	In Absence of Pause	With Incomplete Charging of Condenser $u = 0.85u_0$
N	28	100	220
η	0.007	0.026	0.035

And so, by increasing the number of discharges from 28 to 220 per sec, in the case of operation with a 500-mfd condenser, productivity may be increased. Further increase of the number of discharges lowers productivity.

The optimal number of discharges (17) depends on current intensity, capacitance, and voltage.

For ordinary voltages and capacitance, it is easy to determine the number of discharges giving maximum productivity by using Table 11.

Table 11. Coefficient by Which Current I is Multiplied to Determine Optimum Number of Discharges Yielding Maximum Productivity

C (mfd) Voltage (v)	5	25	50	100	200	300	400	500
80	1360	272	130	68	34	43	17	14
120	907	181	90	44	43	16	12	9
160	680	136	68	34	17	12	9	7
220	544	109	54	28	14	9	7	6

Taking the magnitudes of current intensity established in practice (Table 2), we obtain the number of discharges (Table 12) with which the electric spark equipment should give the highest production (Table 13). Maximum productivity is

$$Q = q \cdot 0.85^3 N \cdot 60 = 36.6 q \cdot N \qquad (19)$$

where q is the discharge productivity determined according to Table 6, and N is the number of discharges determined by Table 8.

Table 12. Optimum Number of Discharges per Sec for Facilitating Maximum Productivity of Electric Spark Installation

C (mfd) Voltage (v)	5	100	300	500
80	1088	884	736	630
120	725	590	485	405
160	544	442	384	315
220	435	357	294	252

Table 13. Greatest Productivity (in cu mm/min) with Discharges of Condensers Charged up to $u = 0.85\ u_0$

C (mfd) Voltage (v)	5	25	50	100	200	300	400	500
80	1.2	20	90	300	1000	1600	2000	2400
160	8	100	260	750	1800	2000	1900	2000

Other Methods of Increasing Productivity

The high specific productivity of electric spark cutting (q = 165 cu mm/min) is a reliable basis for increasing per-minute productivity and bringing it to values higher than those for mechanical cutting. For this, the same methods should be used as in mechanical cutting. The low specific productivity of milling (q = 70 cu mm/min), as is well known, does not prevent attaining a per-minute productivity second only to that of drawing. In milling, high per-minute productivity is attained by increasing the length of the cutting edge (by an increased number of teeth in the cutter, and a longer active part of the teeth). The realization of this method in electric spark cutting is complicated.

Productivity is not affected by increasing the active surface of the electrode; the spark discharge cycles and the dispersion of metal take place in consecutive order. As a rule, parallel discharges do not occur.

The verified method in electric spark cutting is the use of a composite electrode. Current from the corresponding condenser is fed to each element of the composite electrode E (Figure 3). Each condenser is charged through a separate resistor.

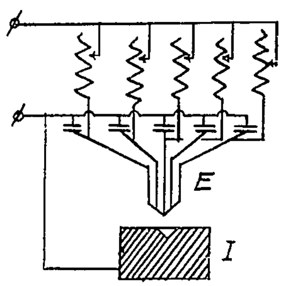

Figure 3

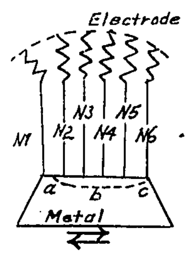

Figure 4

To isolate the parts of the electrode, two layers of paper (blueprint) of the general thickness of 0.25 mm may be used. This is sufficient spacing to keep the separate elements from touching. At the time of operation, the paper burns out to a depth of 1 mm in the space between the elements, so that it does not impede the cutting process. The electrode cross-section should be 3 sq mm for a crater diameter of $d = 2$ mm.

Attempts to apply this principle of multielectrode cutting in our work were not successful at first. In approaching the work, one of the electrodes, (for example, 1 in Figure 4) makes contact with the metal. The spark discharges between electrodes 2 to 6, on the one hand, and the metal, on the other, continue until the spark gap abc between the electrodes and the craters increases to the point where a discharge is impossible. The observations show that at the beginning of cutting the discharges follow one another at frequent intervals, but then they become increasingly sparse until they cease altogether. To continue the cutting process it is nececessary to disconnect electrode 1 from the metal. Then, as the spark discharges between electrode 1 and the metal wear out the electrode, the other electrodes come into play. But after a few seconds, contact again takes place between one of the operating electrodes and the work piece. As a result, in the first experiments with multielectrode cutting, there was a decrease in productivity instead of the expected increase. Investigation showed that the usual connection of the regulating solenoid to the supply rheostat of the condenser does not affect the described condition.

The use of a vibrator in any form is an effective method. The vibrations or movements of the electrodes in relation to the metal prevent any lengthy contact of any of the electrodes with the metal. However, contacts which are inevitable even with this method lower the efficiency of multielectrode cutting.

Electronic Control of the Electric Spark Cutting Process

The author devised a system of electronic control (Figure 5) for electric spark cutting and introduced it at one of the factories. This system is still the only one which assures efficient multielectrode cutting.

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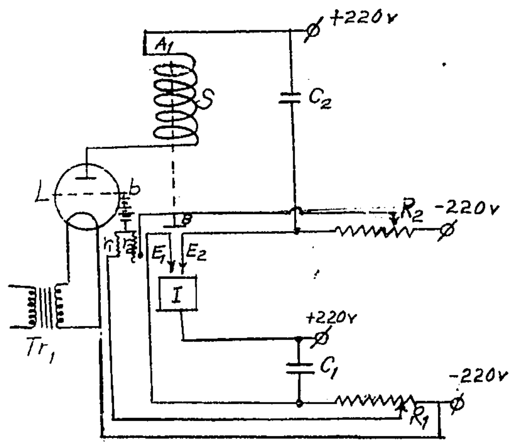

Figure 5

Electrodes E_1 and E_2 are firmly fastened to spindle AB. This spindle is the core of solenoid S. It has only one motion (in the axial direction) and increases and decreases the spark gap between electrodes E_1 and E_2 and the metal I. The gap is controlled by regulating the current flow in solenoid S which increases or decreases the drawing power of the solenoid.

Solenoid S is fed with the plate current of a triode or pentode. The plate current of tube L is controlled by varying the voltage between the grid and the filament. This voltage is taken from rheostats R_1 and R_2 and applied through resistors r_1 and r_2 to the grid or tube L. The regulation of the supplementary voltage from the grid battery b and of the resistances of r_1, r_2, R_1, and R_2 permit the choice of operation on any part of the characteristic curve of the tube and consequently establishing the best operating conditions for electric spark cutting. As an example of operating on the indicated production system, the cutting of an opening 40 x 9 mm in a plate of stainless steel 20 mm thick can be used. The productivity of electric spark cutting was 4 times greater than that of mechanical cutting. Average conditions were used: supply $u \approx 200$ v, short-circuit current for each electrode $I_k = 15$ a, capacitance of the condenser $C = 260$ mfd. A Type U0186 tube was satisfactory for the work.

The tube was supplied as follows: filament supply from transformer Tr 220/4 v, plate supply from the same 220-v converter installation previously referred to, grid bias (20 v) from the battery B. The resistors r_1 and r_2 200 ohms. The leads to the grid of the tube are taken from the resistors R_1 R_2 12 ohms.

Normal work is done with a current $i = 120/200$ ma passing through the solenoid (20,000 turns of wire, $d = 0.35$ mm). Upon short-circuiting the electrode E with the metal, the current sharply increases, and the solenoid receives a drawing power sufficient to break the short circuit and thus assure a continuity of the spark process. The described principle permits the connection of a large number of electrodes. This eliminates the necessity of interfering with the operator during the process of working the metal. Thus, the machine is semiautomatic.

The use of the described theoretical foundations of electric spark cutting in production made it possible to solve many difficult problems. Thousands of parts were successfully made by electric spark cutting. Many parts of complex structure were made very simply. A conical opening of rectangular cross-section with complex cross-overs is an example. Here the electric spark processing was the only acceptable production method. The broad and rapid dissemination of the described methods is one of the most important problems for technologists and designers of our machine-building industry.

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